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A study of the quality of surface windspeed and wave height observations from sea stations.

by

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February 1995

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Abstract

Wave height and surface windspeed observations are made at both manned and automatic sea stations; these include buoys, ships and platforms. Wave height is reported as either a significant wave height or as separate windsea and swell heights. This study looked at the quality of these *in-situ* observations and assessed their potential usefulness in operational wave forecasting. The quality of *in-situ* observations was compared against that of ERS-1 altimeter observations and observations made at reliable buoys; the UKMO global wave model was used as a reference. Observation minus model mean bias and standard deviation statistics were calculated for each group. Observations received at UKMO in February 1994 were studied. Results showed that stations which reported significant wave height did so with an accuracy similar to that of reliable buoys and ERS-1; windspeeds were slightly over estimated. Stations which reported windsea and swell heights over estimated both wave heights and windspeeds. Assimilation of these observations should take into account their error characteristics.

1. Introduction

Sea state and surface wind observations are made at both manned and automatic sea stations. These *in-situ* observations made by buoys, platforms and ships are stored by the UK Met.Office (UKMO) on the Synoptic Data Bank (SDB). This paper describes a study carried out to assess the quality of *in-situ* observations, and their potential usefulness in operational wave forecasting. Section 1 is this introduction, Section 2 gives details of the type and quantity of observations available, Section 3 describes the method used to assess observation quality. Section 4 contains results of the assessment, and finally Section 5 summarises and gives recommendations on how these observations may be put to use.

2. Observations

2.1 Type of observations.

Reports of surface observations made at sea stations are received by the Met.Office and are stored on the SDB. WMO code FM13 is used which is capable of holding observations of many different meteorological parameters (WMO Manual on Codes, No.306). Sea stations have either a number call sign or a character call sign; ships use character call signs, buoys use number call signs, platforms use either character or number call signs. The type of call sign determines whether a platform has been treated as a buoy or a ship in this study.

For the purposes of this study only observations of the following have been considered: significant wave height, windsea height, swell height, and windspeed. These parameters were chosen because the UKMO wave model data assimilation scheme requires collocated observations of wave height and windspeed, both of which must be good quality. Significant wave height is a measure of the total sea height and is defined as the average height of the ⅓ highest waves. Windsea is defined as that part of the total sea height which is a direct result of the local wind blowing at that time. Swell is that part of the total sea height which is not caused by the local wind, and includes for example waves created by distant storms which have then travelled to the observing position. Up to two independent systems of swell can be reported, each with a height and direction of travel. (WMO Nos. 8, 702 and 306).

Reported windspeed observations are either visual estimates or, where an instrument is available, are anemometer readings. In either case reported windspeed observations should be the windspeed at a standard height of 10m, (WMO No.8). A buoy anemometer should be mounted 10m above the water-line and so report

a standard '10m wind'. Platform anemometers should be mounted at least 10m above the top of the tallest obstruction on the platform. A ship should position its anemometer as far forward and as high as possible, such that local effects produced by the ship's structure are minimised. Windspeed measurements at heights other than 10m should be adjusted to the standard '10m wind'. Unfortunately information on instrument positioning is not easily available for individual stations.

2.2 Number of observations.

The number of useful observations received each day is fairly constant at around 1100 buoy observations and 1700 ship observations. The term 'useful' is used here to describe observations which satisfy conditions imposed by quality control (see 2.6). Figure 1 shows the number of useful observations received each hour on one day, 16th January 1994. Most buoys report hourly, although some report only at 3 or 6 hour intervals. Most ships report every 6 hours with a small number reporting more frequently. Table 1 gives the number of reports made on this day containing the different types of wave height information. Most buoys report only significant wave height, with a small number of platforms reporting windsea and swell information. Few ships report significant wave height; the majority report windsea and swell heights only.

2.3 Station locations.

Figures 2a & 2b show the positions of the buoys and ships reporting observations over a 24 hour period. The geographical spread of buoy data is poor; buoys are positioned mostly in the Northern hemisphere near to coasts. Around Europe there are several stations in the North Sea but few elsewhere. The distribution of ship data is much better. Ships are not limited to coastal regions; cross Atlantic and Pacific shipping routes can be seen. There is good coverage of the Northern hemisphere, including the European area. Coverage of the Southern hemisphere is not as good but is nevertheless a great improvement over buoy data.

2.4 Time of receipt.

Each station report holds the time of receipt of the report onto the SDB at UKMO. From this and the validity time of the observation a delay time can be calculated. There is obviously a time lag between an observation being made at sea and its arrival on the SDB. Observations for which a negative delay time is calculated have been made and reported early; observations with a positive delay time may well have been made early in order to arrive close to validity time; no part of code FM13 indicates actual observation time. Figure 3 shows the delay time of observations received on 16th January 1994. Most observations were received less than 1 hour after their validity time, with numbers of observations arriving later decreasing rapidly: a few observations were received early. On this day one buoy report from buoy 62154, and 33 ship reports from 25 different ships were received early. Observations for the full month of February 1994 revealed some persistent early reporters: buoy

62029 reported 103 observations early, 7 other buoys reported slightly early bringing the total to 119 early buoy reports for the full month. A total of 729 ships reports were made early by 182 ships. Most reports were early by less than 15 minutes.

The time of receipt of reports is important when considering operational assimilation of observations into the wave models. If observations are to be used operationally they must arrive on the SDB in sufficient time to be included in the observation processing step of the operational suite. This step is run at approximately 0330Z and 1530Z each day for the global wave model and at 02Z and 14Z for the European area wave model. Most buoy and ship reports are received in good time.

2.5 Report precision.

Each report holds the precision to which the wave height observations are reported. Significant wave height observations are always reported in units of 0.5m. In some cases the station is capable of measuring more precisely and significant wave height is also reported in units of 0.1m. Windsea and swell heights are reported only in units of 0.5m (WMO No. 306). Where a significant wave height observation is reported to 0.1m precision this has been used in preference to the 0.5m precision observation.

Windspeed is reported in units of either $1ms^{-1}$ or 1 knot. An indicator is set in the FM13 code to indicate in which unit the windspeed is reported and also the source of the observation: either a visual estimate or an anemometer reading (WMO No. 306). Only observations which include a valid observation source indicator have been used. Observations in knots are converted to ms^{-1} before use.

2.6 Observation errors and observation quality control.

Errors in wind and wave observations can occur for a variety of reasons. These include instrument calibration and sensitivity problems, as well as problems associated with visual estimates. Some problems are mentioned here, though the list is not comprehensive.

WMO guidelines state that observations should be made over a certain time period, this may not always be adhered to. There are obvious problems with making visual observations at night time or in poor visibility conditions. Ship and platform windspeed measurements may be affected by poor anemometer positioning and also by the need for manual calculation to correct for ship movement. Visual wave height observations may be affected by observing position, the angle of the sun, or the complexity of the sea state. Waves look flatter and hence smaller from high above; a low sun angle makes waves appear larger; where several wave systems are

present it may be difficult to distinguish separate windsea and swell systems. (Reid and Collen (1983), Wilkerson (1986), WMO No. 702.)

Some quality control of observations is done before they are put on the SDB: checks are carried out on the reported position of each station against a land sea mask and against a recent report by the same station. These checks are referred to as a position check and a movement check. However, these checks are not very reliable: the position check is in general satisfactory, but the movement check is not (Ingleby, 1994). Further quality control checks were performed on observations for the purposes of this study: a crude climatology check, a background check and a more precise position check. Details of these additional observation quality control checks are in Appendix A.

Observations from buoy, ship, and platform sea stations are used in the assimilation step of the UKMO NWP model (Cullen, 1993 and Lorenc et al, 1991). As part of the observation quality control system several blacklists of unreliable stations are used. These are the 'ship wind rejection list', 'ship sea surface temperature rejection list', 'ship pressure correction list', and 'ship pressure rejection list'. Station names are checked against the blacklists before observations are used. In this study observations from stations appearing on any of these lists are treated separately from other observations. The wave model assimilation scheme although not actually assimilating windspeed observations does make use of them, and so excluding observations from stations on the 'ship wind rejection list' is justifiable. Observations from stations on other blacklists are excluded as a precaution, based on the premise that if a station is unable to make accurate observations of one parameter it may give poor reports of other parameters. The validity of this assumption is discussed in Section 4.5.

3. Model data and observation assessment method

3.1 Model data.

Two wave models are run operationally by the UKMO; a global model and a European area model. Only data from the global model, with a resolution of 1.25° longitude by 0.833° latitude, have been used in this study. Model analyses are six hourly at 00, 06, 12, and 18Z. The global wave model is driven by winds from the lowest sigma level of the UKMO operational NWP model, sigma = 0.997, at a nominal height of between 19.5m and 25m. ERS-1 altimeter wave height data are assimilated into the global wave model. Details of the wave model, its assimilation scheme, and comment on the quality of ERS-1 altimeter observations can be found in Foreman *et al* (1994).

3.2 Observation assessment.

In-situ observations were assessed directly against global wave model analyses, and indirectly against observations made at reliable sea stations and by satellite. Thirty-five reliable buoys and platforms are used for operational wave model verification, providing information on the quality of wave model analyses. Figure 4 shows the location of these stations. The stations generally lie close to model coasts and therefore represent the performance of the model close to coasts, rather than over the whole model area. However, the positioning of the stations is such that several different wave climatologies are represented, and the verification statistics do provide valuable information on the quality of model analyses. Figure 5 shows the position of ERS-1 satellite tracks over a typical 12 hour period: the satellite provides good global coverage with observations made at a rate of approximately 1 per second. ERS-1 altimeter wave height observations are made to an accuracy of 0.5m or 10% whichever is greater (Francis *et al*, 1991).

Model fields of significant wave height, windspeed and model grid point type were interpolated to observation positions. Mean observation minus model wave height and windspeed differences were then calculated for each group of observations: all *in-situ* observations, observations made at reliable sea stations, and ERS-1 altimeter observations. Hence, the mean bias and standard deviation calculated for all *in-situ* observations could be compared against statistics calculated for trusted observations.

The grid point type field is used by the wave model to specify whether each grid point is treated as land, coast, or sea. Interpolated to observation position, this indicates the proximity of the observing station to any coast; it acts here as a land sea mask quality control check. Interpolation to positions outside the wave model grid results in a model value set to the missing data indicator; these observations are not used in this study.

3.3 Model analysis times.

Model fields are available only at 00, 06, 12, and 18Z, whereas observations are reported at each hour. Observations made at 00, 06, 12, and 18Z were compared with model fields valid at that time. Observations made at times between these hours were compared with the nearest model data time, between 3 hours earlier and 2 hours later than the time of observation; this could adversely affect the comparison statistics and is discussed in Section 4.3. This is an important point to consider for buoy observations, which are usually reported hourly, but less so for ship observations which are mostly reported only at the main synoptic hours. This grouping of observations around the main synoptic hours could not be avoided given the available archived model data. However, it is worth pointing out that although the grouping is necessary in this comparison, it would not be necessary were observations to be assimilated: observations are used in the assimilation scheme at their observed hour.

3.4 Conversion to significant wave height.

This study used significant wave height data from the global wave model. However, many observations, particularly those from ships, were of separate windsea and swell heights rather than a significant wave height. These observations were converted to significant wave height (swh) before being compared with model fields by using (WMO No. 702),

$$swh^2 = (\text{windsea height})^2 + (\text{swell system 1 height})^2 + (\text{swell system 2 height})^2$$

4. Results.

4.1. Operational wave model verification and ERS-1 comparison.

Observations made for the period 1st to 28th February 1994 have been studied. Table 2 shows statistics calculated for this period for observations made at verification stations (see Section 3.2 and Figure 4) and by the ERS-1 satellite (see Figure 5). The ERS-1 statistics give a better picture of how the model behaves over the whole globe, as compared to the more limited coverage provided by verification stations. However we must bear in mind the fact that ERS-1 altimeter wave height data are assimilated into the global wave model: satellite and model wave heights are not independent. These bias and standard deviation values are used as a guide to the overall accuracy of the wave model, and as such are the values against which *in-situ* observations are assessed.

Both sets of statistics indicate that the global wave model heights were too low; by 0.42m at verification stations, and by 0.13m along the satellite track. This difference may be due to the differences in observation errors or differences in geographical location of observations; standard deviations are similar. The windspeed biases appear to contradict each other; verification stations suggest model winds are too strong, whilst ERS-1 suggests model winds are too light. This contradiction in windspeed bias is certainly in part a consequence of the verification method rather than reality. At verification stations observed windspeeds are compared against bottom model level winds, at a height of approximately 20m, without any consideration of the height at which observations are reported, nominally at 10m. Assuming neutral stability in the lowest model level this verification method will give an observed minus model bias which is unrealistically low. (See Foreman *et al*, 1992 for comment on model windspeed verification). ERS-1 observed winds are correctly compared against model winds interpolated to the observed height of 10m. ERS-1 windspeed statistics are perhaps therefore more realistic. Standard deviations are similar. Details of quality control for verification station and ERS-1 observations are in Appendix A.

4.2 Overall quality of all wave and wind observations.

Table 3 shows observation minus model mean bias and standard deviation statistics for all ship and all buoy observations from 1st to 28th February 1994. Statistics have been calculated separately for observations of significant wave height and observations of windsea and swell. (The observations of windsea and swell are converted to a significant wave height before calculation of the statistics. See Section 3.4) Statistics are compared against those in Table 2.

These statistics for 'all buoys' and 'all ships' suggest that in general both buoys and ships are capable of reporting significant wave height with an accuracy comparable to that of both the verification stations and ERS-1. In each case the mean bias lies between the verification station and the ERS-1 value: the standard deviations are similar. This perhaps reflects the geographical distribution of *in-situ* observations, which itself lies between the extremes of the distribution of the verification stations and the much improved ERS-1 distribution. For observations of windsea and swell the calculated biases and standard deviations are similar for 'all buoys' and 'all ships', suggesting that visual observations made by ships are of similar quality to those made by buoys (visual observations are made at platforms). However, values are greater than those for observations of significant wave height, and also greater than verification station and ERS-1 values in Table 2: this suggests over estimation of windsea and swell heights and more variability in the observations. Some possible reasons for the overestimation of windsea and swell are discussed in Section 4.4.

Comparisons of ship and buoy observations by Laing (1985) and by Wilkerson (1986) also show over estimation of windsea and swell heights by ships. Laing compares collocated buoy and ship observations over several months at three separate locations; results show a mean ship minus buoy wave height bias of 0.5m. Wilkerson compares buoy and ship observations made within 100km of each other; results show a mean ship minus buoy wave height bias of 0.4m.

Model windspeeds were converted to 10m before comparison with observations. The statistics in Table 3 show that for windspeed observations made by buoys and by ships the mean observed value exceeds the mean model value. If ERS-1 observations are assumed to be accurate, then stations reporting significant wave height have in general slightly over estimated windspeed by between 0.1 and 0.2ms^{-1}; stations reporting windsea and swell heights have in general over estimated by over 1ms^{-1}. Wilkerson (1986) noted a windspeed over estimation by ships compared to buoys of between 1 and 2ms^{-1} over the full range of windspeeds. It is noticeable that the windspeed bias and standard deviation values are higher for reports containing observations of windsea and swell than for reports of significant wave height for both buoys and ships.

Table 4 shows windspeed statistics in more detail where observations have been grouped together according to the type of wave height observation and the method used to observe windspeed: anemometer reading or visual estimate. Buoys report significant wave heights and anemometer windspeeds. Most ships report windsea and swell heights rather than significant wave height, with windspeed observations fairly evenly split between anemometer readings and visual estimates. The content of platform reports depends on the availability of instruments at each location: platforms are grouped with buoys or ships depending on callsign. There appears to be a larger discrepancy in statistics between those stations that report significant wave height and those that report separate windsea and swell heights, than there is between instrumented and non-instrumented stations. This may be due to a general difference between the stations in instrument type or instrument positioning, in particular instrument height (see Section 2.1): platforms and ships may have problems with anemometer positioning and in conversion to '10m wind' which buoys do not have. Wilkerson (1986) also noted the similarity between instrumented and non-instrumented windspeed observations from ships.

4.3 Observations at synoptic hours only.

Section 3.3 mentions that model data is only available at 00, 06, 12, 18Z, and describes the potential problem arising from comparison with observations made at other hours. Table 3 shows mean bias statistics calculated for observations made at these synoptic hours only. The statistics are similar to those for all buoy and all ship data suggesting this method of comparison is not invalidated by the reduced frequency of model data compared to the frequency of observations. The only significant difference in the statistics occurs for observations of significant wave height made by ships; the bias and standard deviation are slightly higher when only main synoptic hour reports are assessed.

4.4 Comparison of significant wave height with windsea and swell height observations made at the same station.

There are two ways in which wave height observations may be reported: a significant wave height observation, or observations of separate windsea and swell heights. Either one or both of these may be reported (see Section 2.1). Observations of windsea and swell heights were converted to a significant wave height before comparison with model data (see Section 3.4).

Two data groups were considered: reports from ships containing observations of significant wave height and of windsea and swell heights; and all reports of windsea and swell heights from all ships. Take the first of these groups. The observed minus model bias for observations of significant wave height is 0.23m (standard deviation = 1.25, number of obs = 436, mean observed swh = 1.67m); and for observations of windsea and swell

heights is 0.65m (standard deviation=1.00, number of obs=436, mean calculated swh=2.08m). This suggests that observations of windsea and swell are inconsistent with observations of significant wave height. The difference between these two sets of figures must stem from either the observing capabilities of the station or the limitations of the WMO FM13 code used to make reports. A good observer will be able to report observations of significant wave height, windsea height, and up to two swell heights. The question arises as to whether an observer is able to produce a report which is internally consistent in its wave height information. Significant wave height is reported in units of 0.5m or in units of 0.1m where possible: the 0.1m values are preferred in this study, (see Section 2.5). Observations of windsea and swell heights are reported in units of 0.5m. It is therefore inevitable that rounding will take place, and reports may therefore be internally inconsistent to some degree. We must also consider the fact that observers may be more likely to round up rather than down, for instance reporting a swell height of 1.0m rather than 0.5m. There is also the possibility of 'double counting' where waves are reported as both windsea and swell.

Example: consider the actual wave heights observed at a sea station, two possible reports using WMO code FM13, and the wave height calculated from windsea and swell heights, (see Section 3.4).

	observed heights	Report 1	Report 2
sig.wave height	1.77m	2.0m	2.0m
windsea height	1.2m	1.0m	1.5m
swell height	1.3m	1.5m	1.5m
calc'd sig.wave height	1.77m	1.80m	2.12m

The observer may correctly assess the sea state but is then restricted in the accuracy to which he can make the report by the FM13 code definition. In this example Report 1 has rounded down the windsea height to 1.0m, and Report 2 has rounded up to 1.5m. The calculated significant wave heights then differ from each other by 0.32m, and from the actual sig.wave height by +0.03m and +0.35m. In Report 2 the choice to round up has resulted in a higher calculated significant wave height, which will give a higher positive bias value than Report 1.

The second group of all ships reporting windsea and swell heights gives a bias of 0.52m for calculated significant wave height, (see Table 3, mean calculated swh=2.66m). This bias is slightly greater than that for reliable observations in Table 2, 0.42m. However, the reporting methods used are likely to result in overestimation as described above; this bias should not be regarded as indicating poor quality observing, but rather as a consequence of limited reporting methods.

4.5 Observations from blacklisted stations.

The statistics discussed in sections 4.1 to 4.4 exclude all observations made by stations on the station blacklists (see section 2.6); observations made by blacklisted stations were considered separately and are summarised in Table 5. Three station groupings were considered which are referred to here as groupW, group1 and group2. The groups are defined as follows: groupW comprises all stations on the 'ship wind rejection list'; group1 contains all stations which appear on one and only one of the other blacklists; group2 contains all stations on more than one of the other blacklists. Some decision has to be made about whether or not any of the observations made at blacklisted stations are of high enough quality to use in assimilation. The data were quality controlled before statistics were calculated and so gross errors were already removed. Statistics were calculated separately for each station group in the hope that it may be possible to recommend the use of observations from some blacklisted stations, perhaps those from group1 stations.

It is obvious that observations made at stations in groupW should not be assimilated in the UKMO wave forecast model: good quality windspeed observations are essential to the assimilation scheme which requires collocated observations of wave height and windspeed. The question then arises, 'does the inclusion of a station on any of the other blacklists suggest that the station also reports poor quality wave data?' Statistics confirm that observations made by stations in groupW are poor; there is a large standard deviation for both buoy and ship windspeed observations, ship observations also have a large windspeed mean bias, see Table 5.

For stations in group1 the mean significant wave height bias for buoy observations is high at 2.25m, for ship observations it is low, -0.33m; windspeed bias and standard deviation are also high. These values are not close to those for reliable stations suggesting that observations from group1 stations are inaccurate. Group2 has fewer observations for this period, for which the mean bias and standard deviation values for windspeed and for wave height observations are high. Although inclusion of stations on the blacklists refers to the ability to report other parameters, it appears that windspeed and wave height observations are also poor. Observations made in February 1994 by stations on these blacklists are not good enough to use in assimilation.

5. Summary and recommendations

5.1 Summary

This study has looked at the quantity and quality of observations of significant wave height, windsea height, swell height, and windspeed reported by sea stations. These are the observations needed to assimilate wave height information into the UKMO operational wave model. Observations are reported in WMO code FM13

by sea stations which include ships, buoys and platforms. Observations were grouped into those from buoys and those from ships, platform observations were included as either buoy or ship depending on their WMO call sign. Most buoys report hourly providing observations of significant wave height and windspeed; most ships report 6 hourly and provide observations of windsea and swell heights and windspeed. Only a few stations report significant wave height together with windsea and swell heights. Buoys tend to be located close to coasts, ships cover a much wider area. If observations are to be used in an operational wave forecasting system it is essential that they are received quickly by the forecast centre. Most observations are received onto the SDB at UKMO within 1 hour of observation validity time.

There are known difficulties with making observations at sea and so observations must be quality controlled. Some checks are done prior to placing the observations on the SDB: a movement check and a position check. However, the movement check is not very reliable. It will be desirable to improve the quality control of observations before carrying out assimilation of observations, perhaps using methods described by Ingleby (1994). Observations should also be subject to a background check and a climatology check.

Observations from sea stations were compared against wave heights and windspeeds from the UKMO wave model. The mean observation minus model bias and standard deviation statistics were then compared against the same statistics calculated for trusted observations from buoys and the ERS-1 satellite. The wave model was used as a reference against which to assess the quality of observations. Verification of the wave model against observations made at the reliable buoys indicated that in general model wave heights were too low. Comparison with satellite observations also indicated that the model wave heights were low but by a smaller amount.

The buoys and ships considered in this study were capable of reporting significant wave height with an accuracy comparable to that of verification stations; for windsea and swell observations the bias and standard deviation were greater which could be partly due to the limitations of the WMO code FM13, and the suspected tendency for over rather than under estimation. Comparison of ERS-1 with model windspeed implied that model winds were too light at the bottom model level. Comparison of ERS-1 windspeed statistics with those for *in-situ* observations suggested a possible over estimation of observed windspeed, particularly by ships.

Blacklisted stations were also considered. Observations made by stations on the 'reject ship wind' list were poor quality; windspeed and wave height observations made at stations on other blacklists were also poor and should not be used in assimilation.

5.2 Recommendations

A trial is planned to assimilate *in-situ* data into the European wave model. The choice of which observations to use will be based on the results of this study. It is recommended that significant wave height observations with accompanying windspeed observations from both buoys and ships are used, since these have been shown to be of comparable quality to trusted observations. Observations of windsea and swell heights should also be used although care should be taken to consider the implications of the suspected over estimation of wave height. Observations from blacklisted stations should not be used.

Appendix A

Quality control of wave height and windspeed data used in UKMO operational wave model verification.

Do not use an observation if

- observed windspeed is $0ms^{-1}$ and model analysis windspeed is greater than $5ms^{-1}$.
- observed significant wave height is 0m and model analysis wave height is greater than 3m.
- the magnitude of the difference between observed and model analysis values is greater than $15ms^{-1}$ for windspeed, and 10m for wave height.

Quality control of *in-situ* data assessed in this study.

Observations were quality controlled using wave height and windspeed criteria as above for verification data. In addition observations of wave height greater than 16m were not used.

Interpolation of model fields to observation positions was used as an observation position check. The interpolation calculation results in the missing data indicator (mdi) being set for positions over or very close to land. Observations with interpolated model values set to mdi were not used.

Quality control of ERS-1 data.

Observations were quality controlled using

- wave height and windspeed criteria as above for verification data.
- interpolation position check as above for *in-situ* data.
- another position check comparing observation position against a ⅓° land sea mask.

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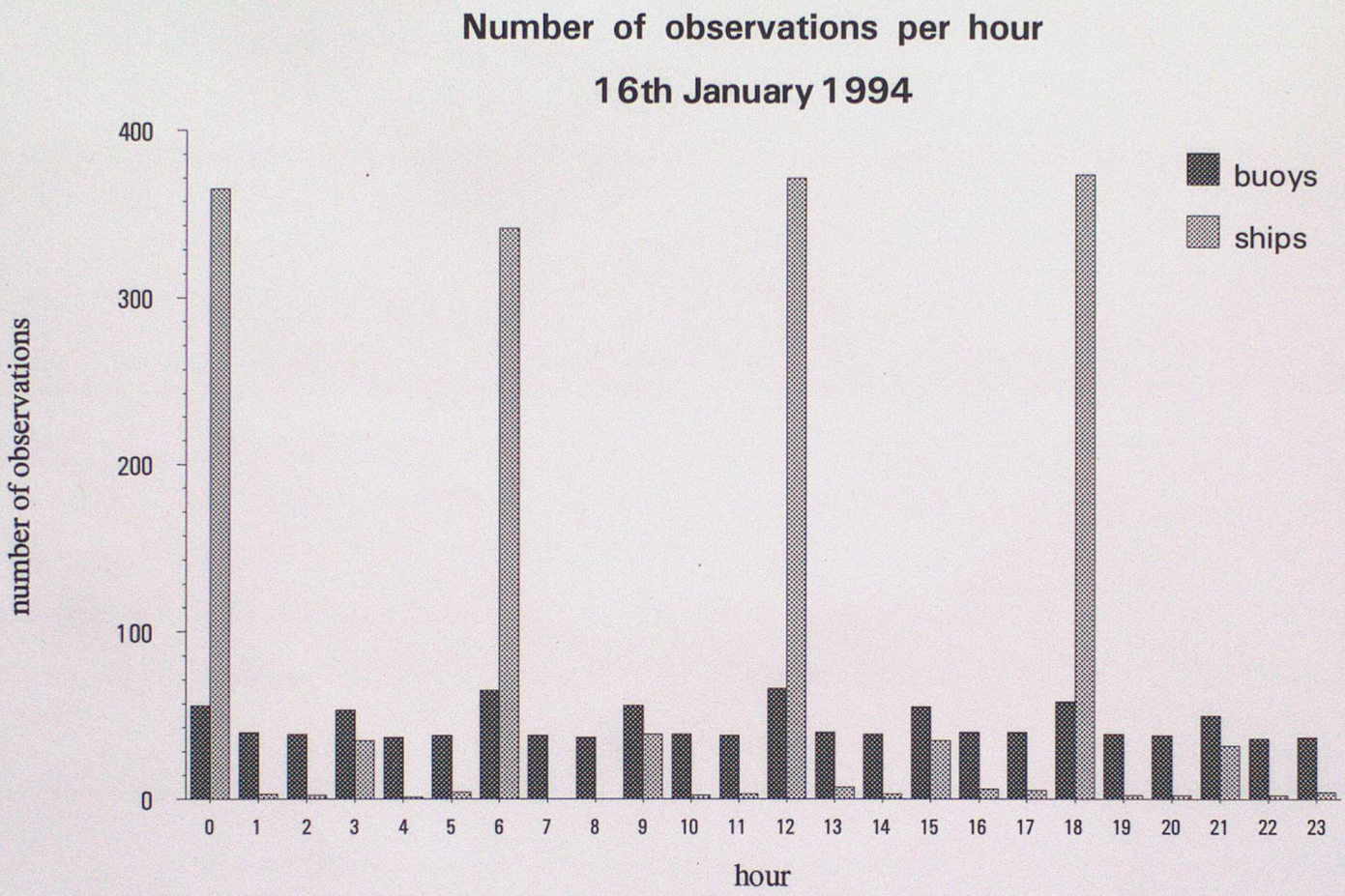
WMO No 702	1988	Guide to wave analysis and forecasting. p 2-1, p 2-4

Figure 1



Number of useful buoy and ship observations received per hour on 16th January 1994
Total number of buoy observations 1074
Total number of ship observations 1617

Figure 2a

Location of buoys reporting in a typical 24 hour period.

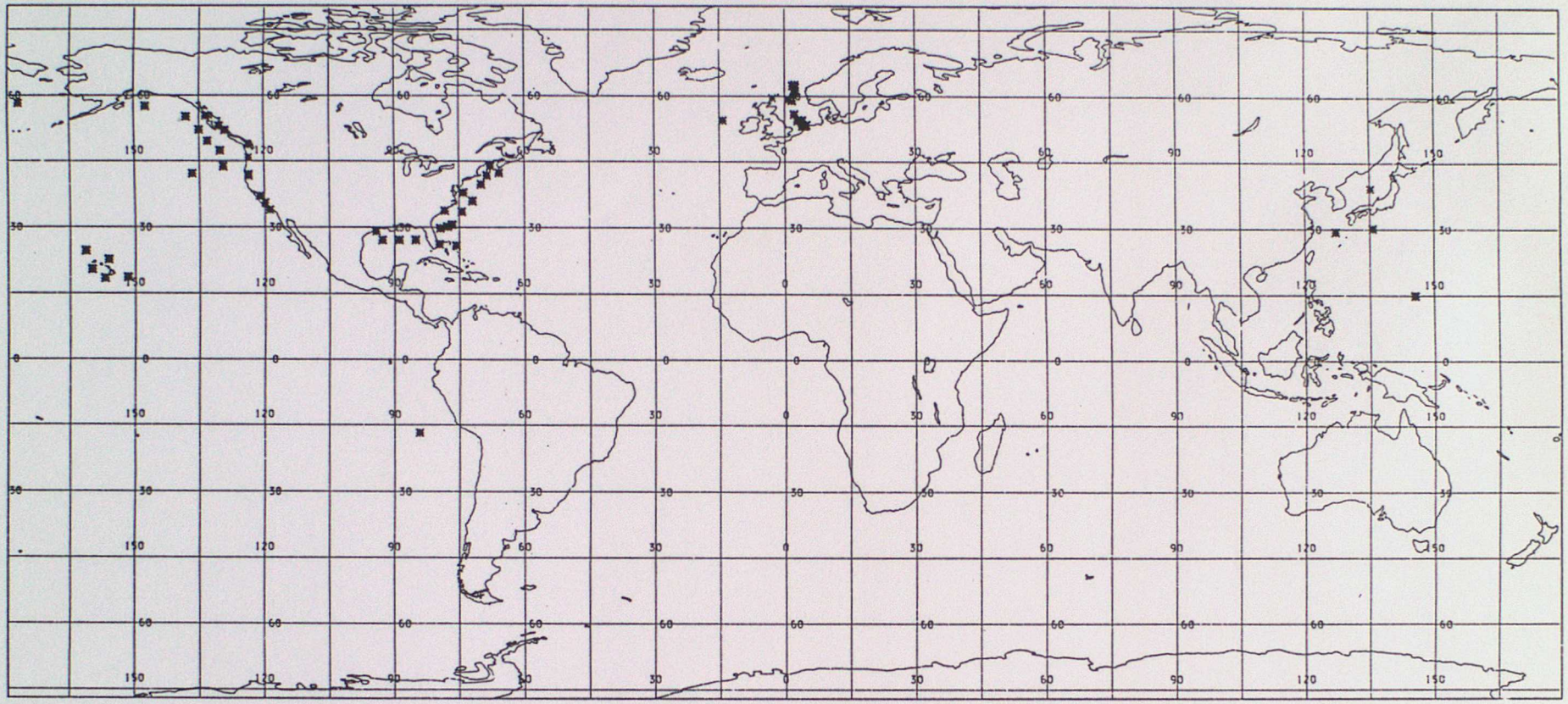


Figure 2b

Location of ships reporting in a typical 24 hour period.

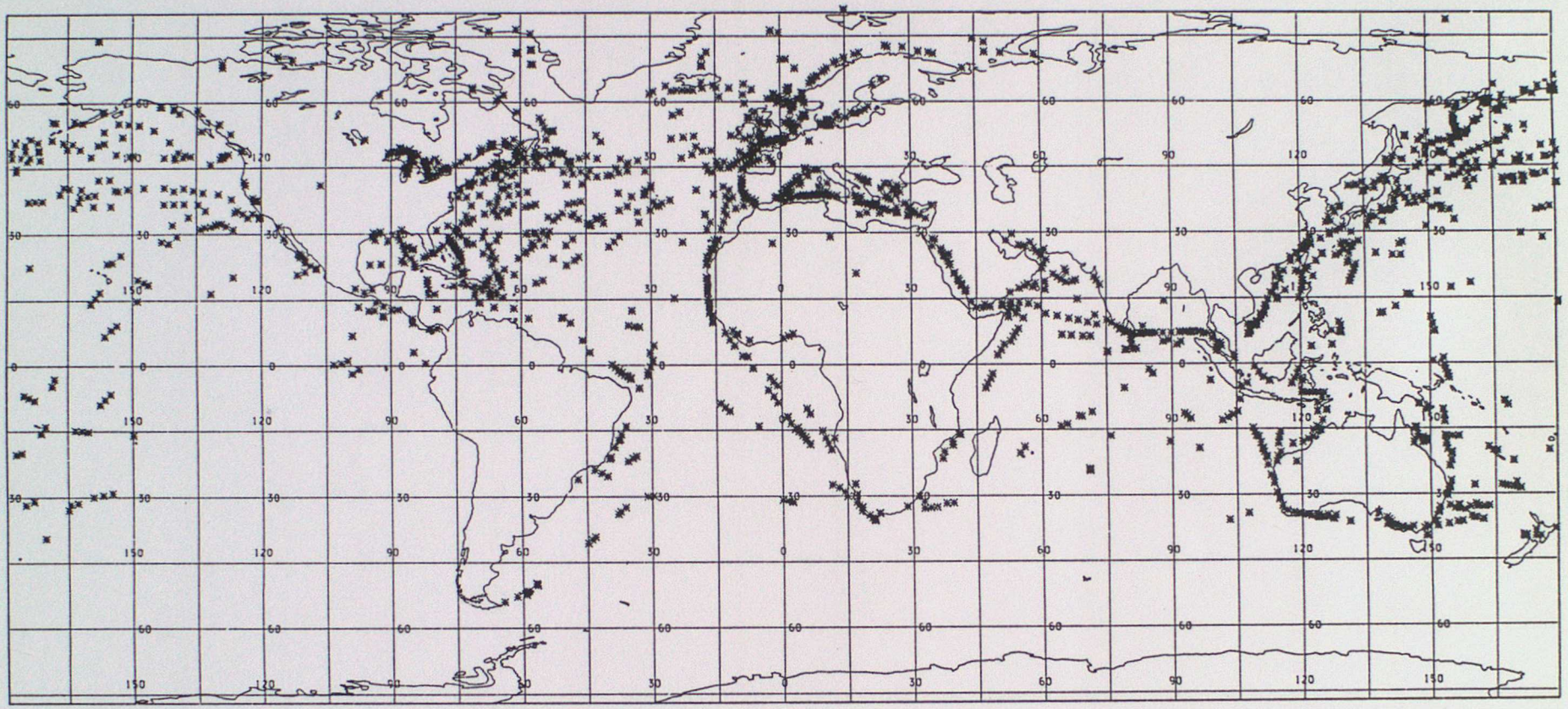
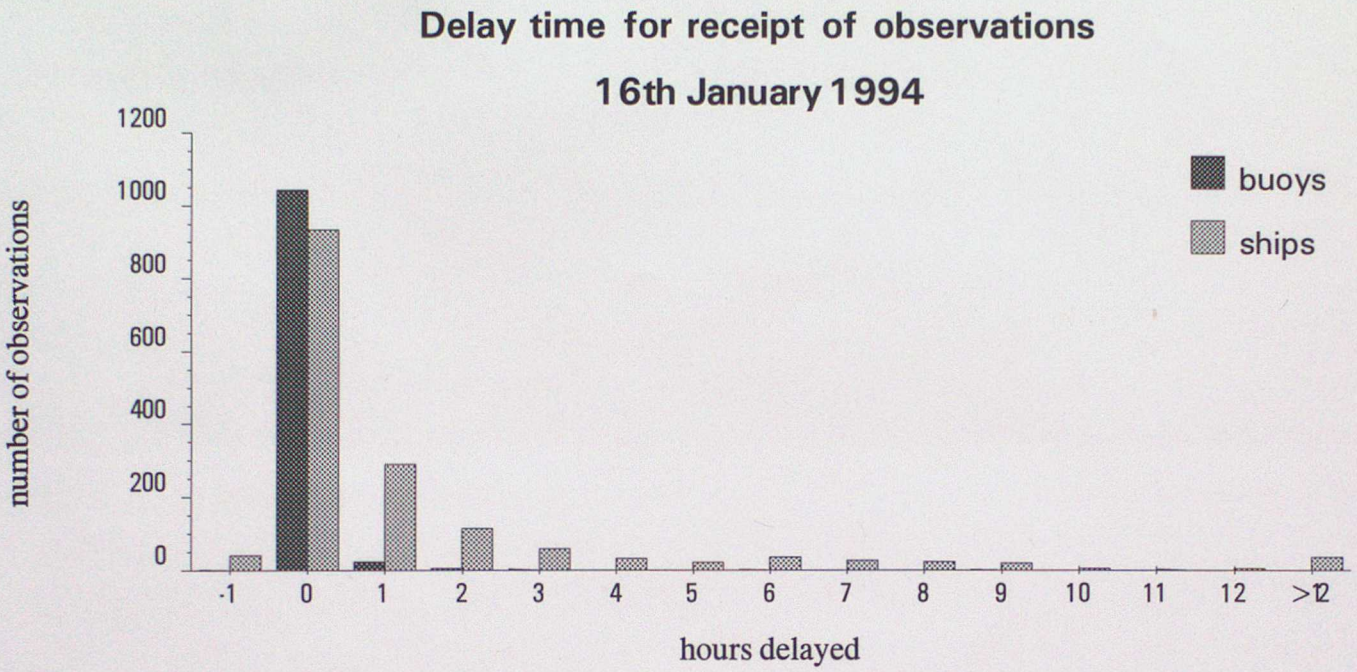


Figure 3



Delay of receipt of observations: validity time minus time of receipt on SDB

Total number of buoy observations 1074

Total number of ship observations 1617

Figure 4

Location of verification stations.

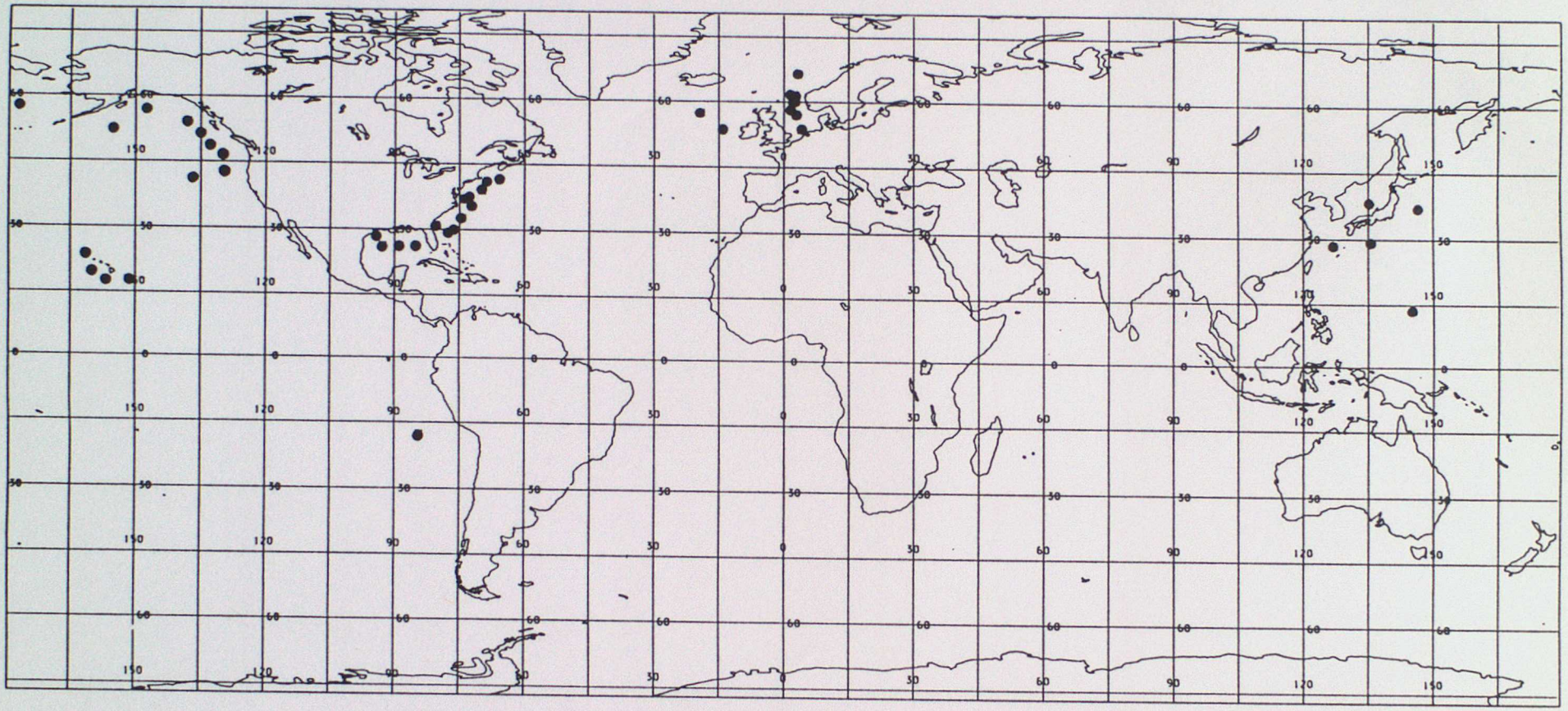


Figure 5

Sample 12 hour data coverage from ERS-1 radar altimeter. Points are plotted at one minute intervals. 00Z - 12Z 10/01/92

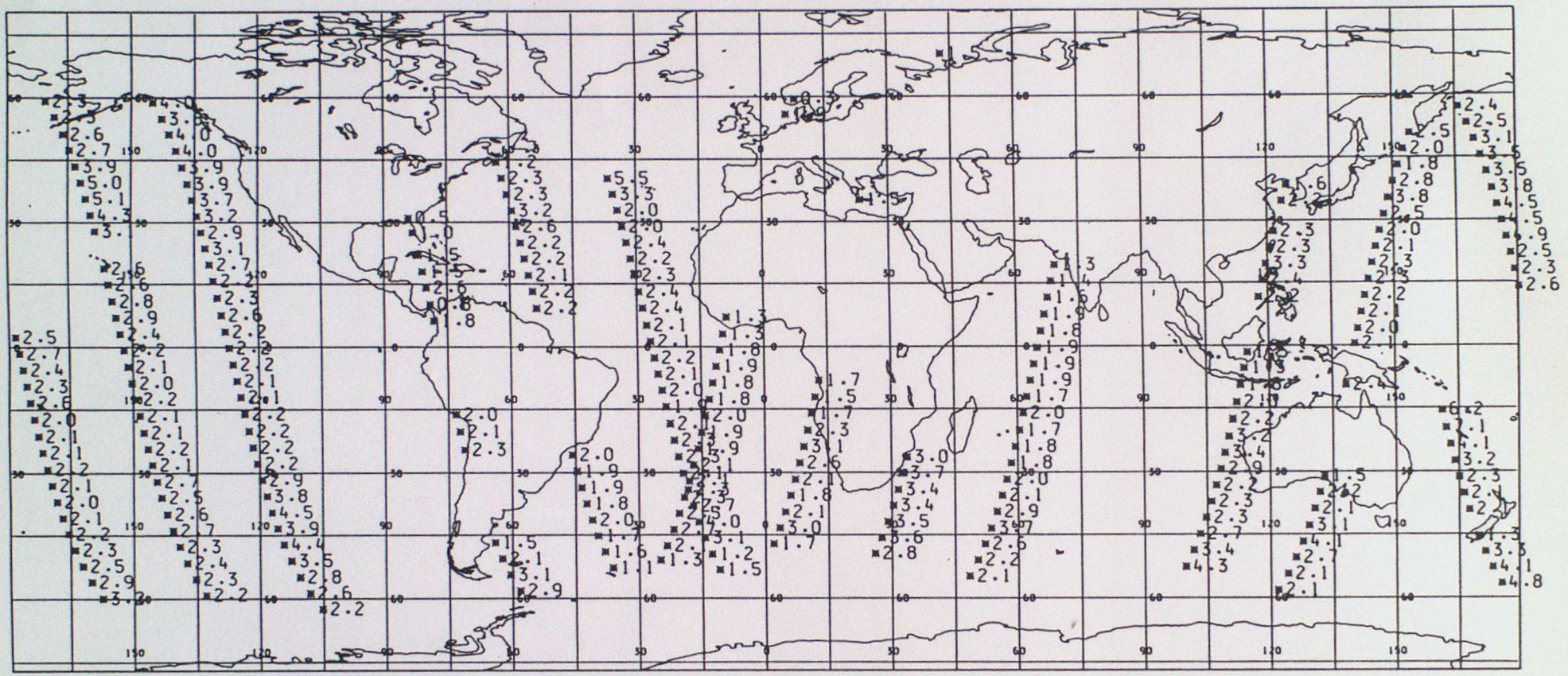


Table 1

Number of reports containing observations of significant wave height and windsea and swell heights. Data 16th January 1994.

#obs	buoys	ships
swh only	999	59
windsea & swell only	56	1552
swh and windsea & swell	19	6
total	1074	1617

Table 2

Mean bias and standard deviation statistics for significant wave height and windspeed (observation - model) at reliable observing stations and at ERS-1 satellite observation positions. Data 1st - 28th February 1994.

	sig.wave height (ob - model) (m)			windspeed (ob - model) (ms^{-1})		
	bias	st.dev	N	bias	st.dev	N
Verif stations	0.42	0.80	3683	-0.27	1.9	3837
ERS-1	0.13	0.90	571218	0.44	2.22	571218

Table 3

Mean bias and standard deviation statistics (observation - model) for significant wave height and windspeed for all buoy and all ship observations, and for observations made at 00,06,12,18Z only. Data 1st to 28th February 1994.

	sig.wave height (ob - model) (m)			**windspeed** (ob - model) (ms^{-1})		
	bias	**st.dev**	**N**	**bias**	**st.dev**	**N**
All buoys swh	0.32	0.77	25245	0.53	1.99	25245
windsea & swell	0.52	1.22	1671	1.80	3.00	1671
All ships swh	0.27	1.01	2238	0.65	2.21	2238
windsea & swell	0.52	1.32	36667	1.67	2.63	36667
00,06,12,18Zonly						
buoys swh	0.33	0.77	5011	0.57	1.89	5011
windsea & swell	0.45	1.21	1176	1.80	2.79	1176
ships swh	0.37	1.29	1037	0.75	2.21	1037
windsea & swell	0.52	1.31	32822	1.65	2.57	32822

Table 4

Detailed windspeed statistics. Mean windspeed bias and standard deviation statistics (observation - model) for buoy and ship observations reporting either significant wave height or windsea and swell heights. Data 1st to 28th February 1994.

	windspeed obs from buoys reporting swh (ms^{-1})			windspeed obs from ships reporting swh (ms^{-1})		
windspeed ob source	bias	st.dev	N	bias	st.dev	N
est m/s			0	6.70	6.11	2
est knots	-2.79		1	2.57	2.50	11
anem m/s	0.65	1.95	18547	1.52	2.14	14
anem knots	0.18	2.04	6697	0.63	2.19	2211
all	0.53	1.99	25245	0.65	2.21	2238

	windspeed obs from buoys reporting windsea & swell (ms^{-1})			windspeed obs from ships reporting windsea & swell (ms^{-1})		
windspeed ob source	bias	st.dev	N	bias	st.dev	N
est m/s			0	2.45	3.26	527
est knots	1.21	2.91	35	1.38	2.54	18905
anem m/s			0	1.84	2.96	3442
anem knots	1.81	3.00	1636	2.00	2.59	13793
all	1.80	3.00	1671	1.67	2.63	36667

Table 5

Observation minus model statistics for observations made at blacklisted stations.

Station groupings:

groupW = stations on the 'ship wind rejection' list,

group1 = stations appearing on one and only one other blacklist,

group2 = stations appearing on more than one other blacklist.

Data 1st to 28th February 1994.

	groupW			group1			group2		
	bias	**st.dev**	**N**	**bias**	**st.dev**	**N**	**bias**	**st.dev**	**N**
buoy swh (m)	1.00	1.81	87	2.25	1.45	728			0
windsea & swell (m)	0.38	1.15	49	0.64	0.97	72			0
windspeed (ms^{-1})	1.47	4.56	129	1.43	2.94	734	2.16	3.92	181
ship swh(m)	0.21	0.65	118	-0.33	0.81	7			0
windsea & swell (m)	0.75	1.64	2218	0.55	1.53	2600	2.00	2.10	179
windspeed (ms^{-1})	3.17	4.20	2333	2.24	3.12	2590	8.45	11.73	2